ARMY RESEARCH LABORATORY

A Review of Previous Works on Observing the Atmospheric Boundary Layer Through Meteorological Measurements

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ARL-MR-448 September 1999

Army Research Laboratory

Adelphi, MD 20783-1197

ARL-MR-448 **September 1999**

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Abstract

This report provides a comprehensive review of some 30 previous works on observing the atmospheric boundary layer through meteorological measurements. I compiled the information in this report from a relatively broad survey of the literature related to field experiments that had focused on processes and events that characterize the boundary layer, and in particular, the boundary layer under atmospherically stable conditions. The summaries that comprise the bulk of the report provide the reader with historical as well as data resource information for several different types of programs on topics from improving weather and climate prediction models to advancing remote sensing platforms and monitoring techniques. Also, the report presents some of the main conclusions derived from two workshop meetings on turbulence and diffusion in the stable boundary layer.

I wrote this report as a result of studying and annotating about 90 references and texts on experiments in the atmospheric boundary layer. It was produced during a period preceding the Cooperative Atmospheric/Surface Exchange Study (CASES-99) program. A colleague suggested that researchers and experimental planners at the Army Research Laboratory might benefit from such an accounting of the scientific objectives, technical goals, and descriptions of the arrays of various sensor platforms that were involved with previous outdoor programs.

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1. Introduction

The boundary layer is a major area of concern in air pollution meteorology. Most of the world's industrial stacks are located within this layer (Gopalakrishnan et al, 1998). The boundary layer also concerns the military because it is, for the most part, the largest portion of the active battlespace. This region of the lower atmosphere is subjected to combat smokes, chemicals, and aerosols. The consequences of smoke and other airborne materials depend not only on their source properties, but also on boundary-layer winds and turbulence (Ohmstede and Stenmark, 1980). It follows that the transport and diffusion of contaminants is related to the mean and turbulent atmospheric state of the boundary layer.

As a rule, the stable boundary layer (SBL)* exists at night when a surface inversion layer forms with warmer air overriding colder air. The SBL grows depending upon (1) the intensity of the winds and wind shear (i.e., mixing the cooler air upward and warmer air downward), (2) longwave radiative flux divergence, which promotes additional cooling of the layer, and sometimes, but to a lesser extent, (3) advection of heat or moisture into the layer. (Advection effects may be due to uneven gradients in terrain, variations in land use, or uneven distributions of vegetation or soil moisture.) Wind speeds are sometimes strong or moderate throughout the nighttime stable period, such as those reported by Garratt (1982); however, more highly stratified layers develop when wind speeds are low. It has been observed that under very stable, low wind-speed conditions, the surface layer meteorology can appear, in effect, to "decouple" from the air flow aloft, becoming more or less dependent on features of the underlying terrain (Businger, 1973; Mahrt, 1985; Nappo, 1991; Howell and Sun, 1998; Mahrt et al, 1998). These conditions, unfortunately, are extremely problematic with regard to atmospheric dispersion† (Sharan et al, 1995).

The mixing process (e.g., overturning) within a stably stratified layer is considerably different from that which results from surface heating (i.e., updrafts and downdrafts). Within the stable layer, vertical displacements are limited, for the most part, to those brought about by broad internal motions or by larger scale wind shear (Hunt et al, 1983). However, sometimes the SBL is observed to produce relatively short-lived, intermittent events, that is, bursts of turbulence in the form of wind gusts and sudden fluctuations in temperature and moisture (Nappo, 1991). It has been reasoned, through analysis of data from acoustic sounders and sensors, that these events result from a complex combination of internal gravity-

*A list of acronyms and abbreviations is provided in the appendix.

†Dispersion is the combined result of transport and diffusion wherein "transport" is considered to be the large-scale advection of the material by wind and "diffusion" refers to the resultant concentrations or spread of the material by turbulence (Ohmstede and Stenmark, 1980).

wave activity, random wind-shear instabilities, and turbulence (Lu et al, 1983). Specific patterns of instability or gravity waves can sometimes be linked to particular mesoscale events or synoptic situations (Zhou Ming-yu et al, 1980, or Neff, 1980). However, with regard to the added mixing (diffusion) of air parcels that occurs due to wave-turbulence interactions, all the current theories, models, and scaling laws break down (ReVelle, 1993).

Some of the difficulties in the collection of data and theoretical description of stable flows are associated with the fact that intermittent behaviors, like turbulent "bursting" and gravity-wave activity, coexist with continuous turbulence structures (Sorbjan, 1988). Continuous turbulence structures are those that are sustained by differential heating, wind shear, and surface stress due to variations in surface roughness, for example. Wave patterns are those that can be launched by terrain obstacles (e.g., a hill or mountain ridge) or those that can result from overturning air above strong wind and wind-shear layers (e.g., a crested wave or breaking wave). These wave-related structures (or events) can be detected by high-frequency FM-CW (frequency modulated-continuous wave) radars, acoustic sounders, and through monitoring of small-scale pressure differences using arrays of microbarographs (Hooke et al, 1972; Hooke, 1979; Lu et al, 1983; Eaton et al, 1995).

Several fairly recent field studies have been conducted to address these issues. For the most part, their objectives have been to improve boundary-layer parameterizations in numerical models (e.g., those used for weather and climate prediction). This report provides a comprehensive review of these programs and approximately 30 previous works dealing with observing the atmospheric boundary layer through meteorological measurements. It was compiled from a relatively broad survey of the literature related to field experiments that focused on processes and events that characterize the boundary layer, and in particular, the boundary layer under atmospherically stable conditions. The summaries that comprise the bulk of this report provide the reader with historical as well as data resource information for several different types of programs on topics from improving weather and climate prediction models to advancing remote sensing platforms and monitoring techniques. Also, the report presents some of the main conclusions derived from two workshop meetings on turbulence and diffusion in the stable boundary layer.

The report was written as a result of studying and annotating about 90 references and texts on the subject of experiments in the atmospheric boundary layer. It was produced during a period when several ARL staff members were considering participation in the CASES-99 program. At that time a colleague suggested that researchers and experimental planners might benefit from such an accounting of the scientific objectives, technical goals, and descriptions of the arrays of various sensor platforms that were involved with the execution of the previous outdoor programs.

2. Turbulence and Diffusion in the Stable Boundary Layer

The U.S. Army Research Office (ARO) and the NOAA Air Resources Laboratory (ARL) conducted a workshop on turbulence and diffusion in the stable boundary layer on 11 to 13 January 1994 at Arizona State University, Tempe, Arizona (Nappo and Bach, 1997). Its goals were to assess research efforts in turbulence and diffusion in stably stratified flows. The workshop conducted meetings on turbulence and gravity-wave interactions, boundary-layer measurements and data analysis, modeling and simulation, laboratory fluid mechanics, and transport and diffusion. In review, the panel found that:

- The SBL is not as easily characterized by time and space scales as its daytime counterpart, the convective boundary layer (CBL).
- Turbulence at night is more often observed as intermittent and sporadic.
- Nighttime events in the boundary layer include wind gusts and bursts of heat, momentum, or pollutant mixing, which are difficult to account for in numerical models using similarity theory.
- Point data (i.e., measurements taken at a single location) may not be representative of the path- or area-average during highly stable periods.
- Bulk-layer models for turbulence* may have undesirable limitations due to unresolved spatial or temporal scales.
- New observation techniques and theories on turbulence structure for stratified flow are needed to account for intermittency events (which are considered a primary mechanism for nighttime turbulent mixing).

A general concern was expressed regarding dispersion under stable, low wind-speed conditions. It was restated that under these circumstances, the SBL is observed to "decouple" from the air flow aloft, becoming more or less dependent on the local terrain, and that the problem then becomes one of weak diffusion and the potential for a build-up of pollutant concentrations in closed basins. On this topic, the panel recommended:

- Continued analysis of existing data from high micrometeorological towers (also discussed in sect. 4 of this report) and
- Field experiments designed to facilitate separations of wave activity from turbulence in the data.

A second workshop meeting on turbulence and diffusion was conducted by the ARO, the Swedish Defense Research Establishment, NOAA's ARL, and the Meteorological Department of Uppsala University (Nappo and

*With regard to bulk-layer turbulence models, Frederickson et al (1998) reported difficulties in modeling the stable case, in particular for applications concerning estimates of atmospheric turbulence-induced refraction.

Johansson, 1998). This workshop meeting was held 21 to 24 October 1997 in Lovanger, Sweden and was attended by 35 scientists from eight countries. Like the 1994 ARO-ARL meeting four years earlier, the panel discussed the distinction between (1) events or effects in a weakly stable layer with high wind speeds and continuous turbulence and (2) events or effects in a very stable layer with low wind speeds and intermittent (bursting, random gusts) turbulence. New analyses of SBL data from the Cabauw site (also discussed in sect. 4.3 of this report) in The Netherlands were presented, wherein it was suggested that:

- Local scaling based on a critical Richardson number and Monin-Obukhov theory, in general, may not apply under very stable conditions.
- There was a need to develop new scaling theory for wave-turbulence interactions.
- Current models would need to be modified to account for the random nature of wave and turbulence interactions.

The panel highlighted the use of NOAA's high-resolution Doppler lidars and turbulence-eddy profilers and recommend continued work on:

- Gravity-wave interactions above and within the forest canopy and their effects on transport and diffusion.
- The increased use of microbarographs for detecting such gravity-wave activity (also discussed by Hooke et al, 1972, and Hooke, 1979).
- Continued measurements of the surface-layer energy budget (i.e., fluxes of sensible and latent heat, ground heat, and radiation flux) because of their importance as an indicator for periods when surface cooling leads to the onset of increased stability.

Improvement of signal processing techniques for remote sensing systems as a means of deriving more reliable turbulence data was also recommended.

3. Earlier Field Projects

Many of the formulations associated with boundary-layer profile and turbulence structure, e.g., the turbulence-scaling variables and calculations for the height of the convective boundary layer and depth of the nocturnal boundary layer, were developed based upon data taken during the earlier field experiments (see table 1). These experiments provided the type of data needed to test and validate the similarity-based models of that time (Webb, 1970, and Dyer, 1974). It was thought that improved numerical parameterizations for surface temperature and wind flow could be applied to studies in air quality, climate, and weather prediction.

3.1 Great Plains Turbulence Field Program

The Great Plains Turbulence Field Program was conducted over a flat and uniform site near O'Neill, Nebraska from 1 August to 8 September 1953 (Lettau and Davidson, 1957). This series of atmospheric surface and boundary-layer experiments was performed by scientists from several universities and U.S. government organizations.* The primary objective of the O'Neill field program was to study wind, temperature, and moisture profile structure in the boundary layer and the surface exchanges of heat, moisture, and momentum through the diurnal cycle. The O'Neill experiment provided a comprehensive data set from which diffusion studies could be performed and theoretical models of diffusion could be developed and verified. The data set included measurements of subsoil temperature, diffusivity, water content, heat capacity, heat storage, and thermal conductivity. It also included measurements of the surface radiation budget, surface stress, microvariations of pressure, and low- and high-frequency measurements of temperature, dew point, wind speed, ozone concentration, and the refractive index. Rawindsonde and radiosonde data (i.e., upper-air soundings) supplemented the data.

3.2 Micrometeorological Expeditions at Kerang and Hay

From 1962 to 1964, five experiments were conducted at Kerang and Hay, in southern New South Wales, Australia to acquire high-quality micrometeorological measurements of wind speed, temperature, and humidity in the 16-m layer above the ground surface. The data set included measurements of the net radiation, the surface fluxes of sensible heat and latent heat, and heat flux into the ground (Swinbank and Dyer, 1968). These expeditions were undertaken by the Division of Meteorological Physics of the Commonwealth Scientific and Industrial Research Organization (CSIRO). The Kerang and Hay data were used to test and validate the various flux-profile (flux-gradient) formulations that had been proposed during that time to characterize the surface layer.

*Participating university groups, government research laboratories, and associate scientific organizations are presented in table 1.

Table 1. A review of previous works on observation of the atmospheric boundary layer through meteorological measurements.

Name	Date range	Place	Group	Reference citation
Great Plains Field Program	1 Aug–8 Sep 1953	O'Neill, NE	Texas A&M, ISC, JHU, MIT, UCLA, UCD, UM, UT, UWI, WHOI, AFCRC, AWS, ANL, WADC, Offutt AFB, TAC-Stewart AFB	Lettau and Davidson (1957)
Expeditions at Kerang and Hay	1962–64	N.S.W., Australia	CSIRO	Swinbank and Dyer (1968)
Wangara Experiment	15 Jul–27 Aug 1967	Hay, N.S.W., Australia	CSIRO, CBM	Clarke et al (1971)
Kansas 1968 Field Program	Jul–Aug 1968	Sublette, KS	AFCRL	Izumi (1968), Haugen et al (1971)
Minnesota 1973 Experiment	Sep 1973	Northwestern MN	AFCRL, AWS, BMO-MRU	Izumi and Caughy (1976), Kaimal et al (1976)
Expeditions at Koorin	15 Jul–13 Aug 1974	Daly Waters, Australia	CSIRO, CBM	Clarke and Brook (1979)
METROMEX	Summers 1971–76	St. Louis, MO	ISWS, UCH, ANL, UWY, IBS, UAZ, PNL, UMR, SRI, NOAA, UCSD, DRI	Changnon (1981)
Sangamon Field Experiments	21 Jul–13 Aug 1975, 16–30 Jul 1976	Sangamon County, IL	ANL	Hicks et al (1981)
International Turbulence Comparison Experiment	7 Oct–2 Nov 1976	Conargo, Australia	CSIRO, UBC, UP, OU, UOP, MRI, KU, ANL, UWA, IAP, UNE, UAD	Dyer et al (1981), Garratt et al (1979)
Marine Surface Layer Micrometeorological Experiments	May 1978 May 1979	San Nicholas Island, CA	NRL	Blanc (1978) Blanc (1981)
SESAME-79	10 Apr–8 Jun 1979 SESAME I: 10–11 Apr 1979	NE, CO, NM, TX, OK, KS, IA, IL, MI, LA, AL, MS, AK, TN	NASA, NSSL, Texas A&M, UVA, NOAA, ERL	Barnes (1979), Gerhard et al (1979), Zhang and Anthes (1982), Mahrt (1985), Sorbjan (1988)
DOE ASCOT Experiments	1979–1988	Anderson Creek Valley, CA; Brush Creek Valley, CO	DOE, WPL, PNL, LLNL, EPS, NOAA, NWS, NCAR	Gudiksen and Dickerson (1982), Orgill and Schreck (1985), Hanna and Strimaitis (1990)
Project PHOENIX PHOENIX II	Sep 1978 15 May–30 Jun 1984	Boulder Atmospheric Observatory, CO	NCAR, UO, NOAA NCAR	Hooke (1979) Lilly (1984)
BLX83	25 May–18 Jun 1983	Chickasha, OK	UWI, ANL, NCAR, NSSL, AWS	Stull and Eloranta (1984)
HAPEX-MOBILHY	1985–1986 SOP: 1 May–15 Jul 1986	Southwestern France	DMN, PNEDC, INRA, INSU, CNES, IH, NCAR, NASA	Andre et al (1986)
First ISLSCP Field Experiment	1987–1989 IFC I–IV: May–Nov 1987 IFC V: 23 Jul–12 Aug 1989	Konza Prairie Natural Area, Manhattan, KS	NASA-GSFC, KSU, NOAA, NWS, NESDIS, WPL, NCAR, USGS, ANL, JPL, NCDC, NRCC, UCAR, UWI, UWA, UWY, UNL, PU, UO, CU, UCO, UG, CSU, AL-A&M, Hydex Corp., Hughes STX	Smith et al (1994), Smith (1998)
Project STABLE	12–17 Apr 1988	Savannah River Site, SC	SRL, NCSU, LLNL	Weber and Kurzeja (1991), Parker and Raman (1993)
Monsoon 90	4–6 Jun 1990, 23 Jul–10 Aug 1990	Walnut Gulch Experimental Watershed, AZ	USDA-ARS, USGS, NASA, UAZ, UM, USU, LANL, JPL, LERTS, CEMAGREF-ENGREF, IRE	Kustas et al (1991)

Table 1 (cont'd). A review of previous works on observation of the atmospheric boundary layer through meteorological measurements.

Name	Date range	Place	Group	Reference citation
FLAT 90	Sep–Nov 1990	Carpenter, WY	NCAR-ATD, NOAA-WPL, NCAR-MMM, CSU	Businger et al (1990), Oncley et al (1996)
Boardman Regional Flux Experiment	Jun 1991	Boardman, OR	PNL, LANL, ANL, ORNL, NOAA-ATDD, UWA, USU, ISWS, BRC, EG&G	Doran et al (1992)
HAPEX-Sahel	1991–1993 IOP: 21 Aug–9 Oct 1992	West African Sahel, Niger River Valley, western Niger	IH, METEO-FRANCE, ORSTOM, CESBIO, LA, DLO, UNI, ACMAD, AGRHYMET, AUW, UM, NASA-Ames	Goutorbe et al (1997), Taylor et al (1997)
Flatland 95 Flatland 96 LIFT	Aug–Sep 1995 Jun–Aug 1996 Jul–Aug 1996	Flatland Atmospheric Observatory, IL	NOAA-ETL, NOAA-ARL, CIRES-CU, NSF, NCAR-ATD	Angevine et al (1998), Cohn et al (1998)
BLX96	15 Jul–13 Aug 1996	OK, KS	UBC, UWY, NCAR, ANL	Stull et al (1997)
BOREAS	Aug 1993–Dec 1996	Thompson, Manitoba; Prince Albert Park, Saskatchewan, Canada	NASA-GSFC, NOAA, NCAR, USDA-ARS, UWY, UBC, UWA, UWI, AES, FC, CCRS, NSERC, NSF, EPA, USFS, USGS, NASA	Sellers et al (1997)
CASES-97	22 Apr–21 May 1997	Walnut River Watershed, Wichita-Winfield, KS	ANL, NCAR, NOAA, ARS, OSU, PSU, CSU, UO, UCO, NASA, UCAR, NSF, EPA, DoD	LeMone and Grossman (1999), Pflaum (1998)
Microfronts Project	Mar 1995	De Graf, KS	NCAR, ORNL, UCO, OSU, ISU, NSF, ARO	Howell and Sun (1998), Mahrt et al (1998), Sun (1999)
JETEX-97	22 Apr–22 May 1997	Jayton, TX; Vici, OK; Haviland, KS	ISU, NCAR, NOAA-NWS	Arrit and Segal (1997), Yang et al (1999)
SABLES-98	Sep 1998	Valladolid, North Castillian Plateau, Spain	CIBA, INM, UB, Risø	Cuxart et al (1999)
CASES-99	Oct 1999	Walnut River Watershed, Wichita-Winfield, KS	ANL, NCAR, NOAA, ARS, OSU, PSU, CSU, UO, UCO, NASA, UCAR, NSF, EPA, DoD	Blumen et al (1998)

3.3 Wangara Experiment

The Wangara Experiment was conducted by a joint team of scientists from the Division of Meteorological Physics, CSIRO, and the Commonwealth Bureau of Meteorology, Melbourne, Australia during the 1967 Southern Hemisphere winter from 15 July to 27 August. Data were collected over an extensive and flat 3600-km^2 area near Hay, New South Wales, Australia. The data consisted mainly of hourly 16-m micrometeorological tower measurements of wind speed, specific humidity, and temperature; hourly surface measurements of the net radiative balance and soil heat flux; hourly pibal (pilot balloon) flights of wind speed and wind direction from 0 to 2 km above ground level; radiosonde (i.e., instrumented balloon-sonde) flights for pressure, temperature, and mixing ratio to a height of 2 km taken at 3 hourly intervals; and reports of fractional, low, high, and total cloud cover, to include cloud type descriptors. These observations were published and contain approximately 1050 hourly reports (profiles) (Clarke et al, 1971).

The principal objective of the experiment was to determine how significant a contribution mesoscale processes (such as cold fronts, thunderstorms, and squall lines) made toward the global circulation of the westerlies* in terms of the horizontal and vertical fluxes of momentum. The experiment was designed to test the contributions of the smaller scale process through the top of the boundary layer in a region of prevailing westerly winds and predominantly north- to south-oriented cold-front passages. Using a network of four pilot balloon stations in a square that was 60 km on a side, the area-average vertical velocities and estimates of vertical momentum transport could be determined and recorded for sufficiently long periods of time. A second objective of the Wangara Experiment was to improve upon the micrometeorological surface-layer data collected during the 1953 Great Plains experiment. It was thought that this large data set, from what was considered an ideal site, would help to resolve many of the remaining uncertainties or ill-defined functions, particularly during atmospherically stable conditions.

3.4 Kansas 1968 Field Program

During July and August 1968, the Boundary Layer Branch of the Air Force Cambridge Research Laboratory (AFCRL) conducted a field experiment over a one-mile-square section of farmland in southwestern Kansas (Izumi, 1968, and Haugen et al, 1971). Measurements of heat flux and momentum flux and vertical profiles of wind speed and temperature were obtained for a wide range of atmospheric conditions and thermal stability. The goal of the experiment was to obtain a comprehensive set of surface-layer turbulence data over a horizontally uniform site. Many similarity (i.e., flux-gradient) verification studies were based on these data, as well as some of the earlier determinations of the spectral characteristics of surface-layer turbulence.

3.5 Minnesota 1973 Atmospheric Boundary Layer Experiment

In September 1973, the AFCRL, the Air Weather Service at Tinker Air Force Base, Oklahoma, and the Meteorological Research Unit (MRU) of the British Meteorological Office, Royal Air Force, Cardington, England, conducted a joint field experiment to study the structure of turbulence in the atmospheric boundary layer over a one mile-square section of farmland in northwestern Minnesota. The primary objectives of the Minnesota 1973 Atmospheric Boundary Layer Experiment (Izumi and Caughey, 1976, and Kaimal et al, 1976) were very similar to those for the 1968 Kansas experiment, that is, to collect heat-flux and momentum-flux data and to make measurements of the vertical profiles of wind speed and

*Westerlies are the dominant west-to-east motion of the atmosphere that is centered over the middle latitudes of both hemispheres (Gedzelman, 1980).

temperature. The difference was that this later full-scale test exploited several new balloon-borne sensing and data reduction techniques as well as several new observational methods to enable the capture of much larger scales of motion and turbulence.

3.6 Koorin Expedition

The Koorin Expedition was conducted from 15 July to 13 August 1974 by a joint team of scientists from the Division of Meteorological Physics, CSIRO, and the Commonwealth Bureau of Meteorology (Clarke and Brook, 1979). In somewhat the same manner as the Wangara program, data were collected over a very large, flat, and relatively featureless area. However, the Koorin experimental site was located in northwestern Australia, near the town of Daly Waters, within a semiarid woodland consisting mainly of low- to medium-height eucalyptus and acacia trees of varying leaf area and density. Its location in tropical latitudes was characterized by predominantly east-to-west winds. The Koorin field site also provided an opportunity to study nocturnal low-level wind maxima that often occur there during the winter. The data collected consisted of hourly radar and theodolite-tracked wind soundings of up to 3 km; radiosonde temperature soundings at three hourly intervals; measurements of wind speed, specific humidity, and temperature profiles from two micrometeorological towers (28 m and 46 m); and measurements of the net radiation, latent heat, sensible heat, and soil heat flux. Aircraft measurements were also made by members of the CSIRO Division of Cloud Physics to supplement the data set. The Koorin experiment contributed to the investigation of the similarity functions used to describe profile structure in numerical models. It also provided data on the nocturnal boundary layer (Garratt, 1983).

3.7 Metropolitan Meteorological Experiment (METROMEX)

The Metropolitan Meteorological Experiment (METROMEX) was a 6-yr multiagency field program conducted during the summers of 1971 to 1976 in St. Louis, Missouri to study the microclimate within and around urban areas (Changnon, 1981). One central issue of the METROMEX program was the effect of an urban environment on the amount and frequency of local rainfall; therefore, one of the program's goals was to identify processes that might cause climate changes due to the differences between urban and rural meteorology. The field project consisted of surface wind field, temperature, and humidity measurements; radar-derived cloud and precipitation measurements; observations of the energy and heat budget; aerosol and trace gas measurements; in-storm aircraft-retrieved data; and profiles of boundary-layer turbulence and thermodynamic data. A large part of the program focused on evaluating the growth of the urban boundary layer in terms of the energy (heat) budget.

3.8 Sangamon Field Experiments

The Sangamon field experiments were conducted by scientists from the Atmospheric Physics Section of the Argonne National Laboratory (ANL) to observe the diurnal evolution of the planetary boundary layer over land (Hicks et al, 1981). The tests were conducted in central Illinois over an extensive and flat region of farmland (mostly maize and soy) in mid-summer. The first experiment from 21 July to 13 August 1975 focused on the breakup of the nighttime stable layer and its transition to a rapidly growing mixed layer through the early morning hours before noon. The second test from 16 to 30 July 1976 focused on the decay of the mixed layer as the day approaches sunset, and the reformation of the surface-layer inversion. Observed data consisted mainly of wind and temperature profiles (similar to those reported by Clarke et al, 1971) and measurement of the surface energy fluxes. The Sangamon data were used to develop and test models of the surface and boundary layer for application to studies in air quality and atmospheric dispersion. The objectives for Sangamon field experiments were motivated by concerns over increases in the use of coal fuel.

3.9 International Turbulence Comparison Experiment (ITCE)

The International Turbulence Comparison Experiment (ITCE) was conducted by scientists from several university and government groups from 7 October through 2 November 1976 at a site near Conargo in southern New South Wales, Australia. The purpose of the ITCE was to compare and assess velocity, temperature, and fast-response humidity sensors used in acquiring high-quality micrometeorological measurements in the 16-m layer above the ground surface. Experimental data were collected over a flat, relatively featureless area, covered mostly by low bushes and native grasses 0.5 m high on average. The turbulence data included measurements of the spectral and cospectral densities of horizontal velocity, vertical velocity, temperature and humidity fluctuations (Dyer et al, 1981). Micrometeorological support data included measurements of net radiation, ground heat flux, evaporation, and surface shearing stress (Garratt et al, 1979). It was hoped that data from the ITCE expedition could also be used in reconciling the various flux-gradient formulations that had recently been proposed (i.e., to complement the results of the Kansas, 1968, experiments).

3.10 Micrometeorological Experiments at San Nicholas Island

Micrometeorological data were collected from 9 to 15 May during the 1978 Cooperative Experiment for West Coast Oceanography and Meteorology (CEWCOM-78) at San Nicolas Island, California

(Blanc, 1978). Scientists from the Naval Research Laboratory (NRL) Atmospheric Physics Branch participated in CEWCOM-78 in support of the Optical Signatures Program funded by the Naval Weapons Center at China Lake. Their main goal was to provide meteorological measurements to characterize the marine surface-layer environment for use during infrared and optical experiments performed during the CEWCOM test.

The May 1979 Marine Surface Layer Micrometeorological Experiment at San Nicolas Island was also conducted by the NRL (Blanc, 1981). During this later experiment, 136 hr of gradient and bulk aerodynamic measurements of momentum, moisture, and sensible heat-flux data were collected in the marine atmospheric surface layer over the Pacific Ocean from an upwind, low-profile promontory. Over a 10-day period, a wide variety of meteorological and oceanographic conditions were observed. Determinations of stability, drag coefficient, roughness length, and sky radiation were recorded as well as mean wind speeds, air-water temperature differences, dew-point water temperature differences, and Richardson number (Ri). About 10 percent of the data were collected under stable atmospheric conditions. The micrometeorological data were also accompanied by 80 hr of aerosol-size distribution observations and twice daily radiosonde measurements for determining the height of the marine inversion. This experiment was also held to characterize the marine layer for applications related to overwater, infrared, and optical refractivity.

3.11 Severe Environmental Storms and Mesoscale Experiment (SESAME-79)

The Severe Environmental Storms and Mesoscale Experiment (SESAME-79) was conducted from 10 April through 8 June 1979 as part of a series of Atmospheric Variability Experiments (AVE) sponsored by the National Aeronautics and Space Administration (NASA). Its main objective was to study spatial and temporal changes in atmospheric profile structure associated with the development of convective systems and thunderstorms (Barnes, 1979). The SESAME-79 data consisted mainly of rawindsonde (radiosonde observation (RAOB)) reports, that is, upper-air soundings taken at three hourly intervals from 23 reporting National Weather Service (NWS) stations and 19 additional reporting stations (Gerhard, 1979) throughout most of the central and southern United States. The data were compiled by scientists from the NOAA Environmental Research Laboratory (ERL), the National Severe Storms Laboratory (NSSL), Texas A&M University, St. Louis University, and the NASA Marshall Space Flight Center (MSFC). In addition to the environmental severe storms program, scientists from the National Center for Atmospheric Research (NCAR) and the University of Virginia collected boundary-layer aircraft data (e.g., temperature, wind velocity, and humidity measurements), tethered balloon, and acoustic sounder data to

investigate vertical structure and turbulence over sections of central Oklahoma (Mahrt, 1985; Sorbjan, 1988). The experiment provided data for research to improve regional-scale forecasts of severe storms (Zhang and Anthes, 1982).

3.12 Department of Energy (DOE) Atmospheric Studies in Complex Terrain (ASCOT) Experiments 1979 to 1988

The Department of Energy (DOE) Atmospheric Studies in Complex Terrain (ASCOT) experiments were conducted from 1979 to 1988 (Hanna and Strimaitis, 1990). The experiments were held primarily at two locations, Anderson Creek Valley near Geysers, California, and Brush Creek Valley, Colorado. The main goals of the ASCOT program were to (1) gain a better understanding of transport and diffusion processes within and around complex terrain, that is, for predominantly terrain-influenced flows, and to (2) provide data and insights toward evaluating the performance of air-quality assessment models (Gudiksen and Dickerson, 1982; Orgill and Schreck, 1985). The main focus of DOE diffusion studies at that time was nocturnal drainage flows through the mountain-valley regions of the western United States (regions that had been identified for the development of fossil fuels). Scientists from several universities and national laboratories participated in the experiments that included the use of instrumented tethered balloons, Doppler acoustic sounders, vertical turbulence profilers, instrumented micrometeorological towers, surface energy budget stations, dual Doppler lidar, upper-air sounding balloons, gas tracers, surface gas-tracer samplers, and gas-tracer profilers.

4. Micrometeorological High Towers

4.1 Brookhaven National Laboratory (BNL)

Mean wind and temperature measurements have been taken for more than 40 years on the 126-m micrometeorological high tower at the Brookhaven National Laboratory (BNL) in Upton, New York. BNL was founded in 1947 on the site of the U.S. Army's former Camp Upton by Associated Universities, Inc., under contract to the Atomic Energy Commission. The high tower at Brookhaven is located 60 miles east of New York City, in Suffolk County, on Long Island. The terrain in the immediate vicinity of the tower site is relatively flat. The vegetation around the site is uniform for a radius of several kilometers and consists mainly of pine and oak trees that are 8 m high on average. In the early 1960s and 1970s, data analysis to assess the applicability of similarity profile relationships, particularly those needed to characterize profile structure over rough terrain and during stable conditions, was performed by members of the BNL Atmospheric Sciences Division under contract by the U.S. Energy

Research and Development Administration (formerly the Atomic Energy Commission, now the U.S. Department of Energy).

At that time, analysis of the data had suggested that the log-linear relationships were valid, even for strongly stable conditions. Gravity-wave interactions that had been cited as the primary reason for the breakdown of such formulations were not disputed, but were thought to be negated by long (approximately 1 hr) wind data-averaging times and by the very rough (forested) surface boundary of the surrounding area (Sethuraman and Brown, 1976).

4.2 Boulder Atmospheric Observatory (BAO)

The Boulder Atmospheric Observatory (BAO) supports a 300-m micrometeorological high tower. The BAO tower is located about 25 km northeast of Boulder, Colorado (and 30 km east of the foothills of the Rocky Mountains) in an area that is generally considered flat. Vegetation around the site for a 3-km radius is low cropland (e.g., wheat or wheat stubble) with few trees or houses. Wind and temperature instrumentation at each of eight levels (10, 22, 50, 100, 150, 200, 250, and 300 m) is identical and records both the mean and fluctuating parts of the meteorological variables (Korrell et al, 1982). The tower's sensor systems include three-axis sonic anemometers, propeller-vane anemometers, fast-response platinum wire and slow-response quartz thermometers, and cooled-mirror dewpoint hygrometers. Also a network of microbarographs centered about the high tower (measuring pressure fluctuations) and two acoustic sounders are used to detect internal waves propagating through the site (Lu et al, 1983).

Researchers from the Wave Propagation Laboratory (WPL) had conducted a series of five studies of the nocturnal boundary layer at BAO in 1981 and 1982 (Kaimal, 1983). These experiments focused on the study of gravity waves propagating through the site. They were also held to collect the type of data needed to determine some of the characteristics that might be of practical importance to the study of transport and diffusion under stable conditions (i.e., general flow characteristics of the nighttime stable layer).

Two earlier field programs were conducted at BAO by scientists from NCAR, NOAA's WPL, and the NSSL: the 1978 PHOENIX project held in September (Hooke, 1979) and PHOENIX II held from 15 May to 30 June 1984 (Lilly, 1984). The PHOENIX projects were designed to test and compare new instrumentation for gathering boundary-layer data, such as radars, lidars, and acoustic sounders. The goal of the PHOENIX experiments was to obtain data for the dry convective boundary layer and the cloud-topped boundary-layer environments. During PHOENIX II, boundary-layer processes and events were observed while demonstrating the use of several newly developed NWS Doppler radar systems.

4.3 Cabauw

The 213-m micrometeorological high tower at Cabauw near De Bilt, in the western part of The Netherlands, was built under the direction of the Royal Netherlands Meteorological Institute (KNMI) specifically for meteorological research and has been in operation since 1973 (Monna and van der Vliet, 1987, and Wessels, 1984). The region surrounding the high tower site is mostly agricultural, with few built-up areas within a 15-km radius. The area is also flat, where changes in surface elevation over 20 km are just a few meters (Van Ulden and Wieringa, 1996).

The tower at Cabauw is a closed cylinder structure 2 m in diameter, with an elevator inside. It carries instruments on 9.4-m booms (in three directions at each level) at 20-m intervals. Each boom can record 60 signal channels, such as temperature, wind speed, humidity, visibility, turbulence, and transmissometer data, for example. Van Ulden and Wieringa (1996) report on the analysis of surface and boundary-layer data taken at the Cabauw site concerning developments in similarity theory and studies of the stable boundary layer that include evolution of fog layers, surface-layer inversions, and applications in air pollution. Data from the Cabauw site have also been used to evaluate weather and climate models, for example, the Project for the Intercomparison of Land/Surface Parameterization Schemes (PILPS) reported in Beljaars and Bosveld (1997).

5. Later Field Projects

The primary goals of the later field projects fall into two broad categories: (1) those aimed at studying turbulence and mixing processes in the convective (or stable) boundary layer, and (2) those that began to focus on improving the current understanding of boundary-layer processes that influence regional and global climate. The first category of field programs focused on producing data that could be used to improve models of the boundary layer for applications in air quality, transport and diffusion of mixed-layer gases, cloud formation, and storm development. The second category of experiments focused on the use of aircraft- and satellite-retrieved information to improve meteorological forecast and climate prediction models (e.g., for surface meteorology, energy and water balance, precipitation, soil moisture content, and environmental chemistry).

5.1 Boundary-Layer Turbulence and Mixing Processes

5.1.1 Boundary Layer Experiment 1983 (BLX83)

The Boundary Layer Experiment 1983 (BLX83) was conducted from 25 May through 18 June near Chickasha, Oklahoma to study interactions between the boundary layer and fair-weather cumulus clouds, and in

particular, how these types of interactions affect aerosol concentrations and the ventilation of pollutants through cloud tops (Stull and Eloranta, 1984). Scientists from the University of Wisconsin Department of Meteorology, the ANL, the NCAR, and the NOAA National Severe Storms Laboratory (NSSL) performed measurement of predominantly daytime, convective boundary-layer turbulence structure. The field experiment focused on measuring the characteristic fluxes and meteorological profile structure at the top of the mixed layer, within and above the entrainment zone,* and through the base of the cloud-topped inversion. Instrumentation used during BLX83 included a Doppler sodar (sonic detection and ranging) system, a micrometeorological tower carrying fast-response turbulence and chemistry sensors, a kytoon† system, portable automated mesonet (PAM II) stations, lidar, aircraft, the NSSL Doppler radar, surface automated mesonetwork (SAM) stations, instrumented television tower, and NWS reporting RAOB (rawinsonde) observations. The unmanned PAM II stations provided the standard surface meteorological variable of mean pressure, temperature, humidity, rainfall, and wind speed and direction. During the BLX83 experiment, the PAM II stations also provided net radiation data (Stull and Eloranta, 1984). The NCAR Queen Air aircraft made 20 flights over the main field site area instrumented with a turbulence gust probe, forward- and side-looking automatic cameras, a liquid water content sensor, a microwave refractometer, visible and IR radiometers, fast-response resistance thermometers, and a fast-response hygrometer (Stull and Eloranta, 1984). Supporting measurements that were taken included the surface fluxes, mixed-layer growth, advection of heat and moisture, and subsidence. Analysis of these data was expected to provide information that could benefit studies in air quality, storm prediction, and airline flight safety, for example.

5.1.2 *Project STABLE (Stable Boundary Layer Experiment) Field Program*

The Savannah River Laboratory Project STABLE (Stable Boundary Layer Experiment) was an SBL turbulence and diffusion study over uneven terrain (Weber and Kurzeja, 1991). Project STABLE was conducted on three nights from 12 to 17 April 1988 by researchers from the Department of Energy Savannah River Laboratory (SRL), North Carolina State University (NCSU), and Lawrence Livermore National Laboratory (LLNL). The Savannah River is located in a region that consists mainly of slightly rolling forested hills, small lakes, agricultural clearings, and swamps. The

*Entrainment is a term used to describe the mixing process at the boundary-layer top, whether it is induced by convective means, i.e., overshooting thermals into the more stable layer aloft, or wind-shear-induced overturning or a combination of both.

†A kytoon is a balloon-borne sensor system used to maintain meteorological instrumentation aloft at approximately a constant height (Huschke, 1959).

Project STABLE experimental site was largely within a 15- to 30-m pine forest about 18 km south of Aiken, South Carolina. The objectives for the Project STABLE field program were to (1) determine the frequency and distribution of turbulent events (also discussed in sects. 1 and 2 of this report) that occur within the nighttime stable layer, (2) determine the validity of current models and theory for such events, (3) study the effects of wave-turbulence interactions on the dispersion of chemical contaminants, and (4) determine how to develop better parameterizations for SBL models and simulations. The field data consisted of measurements from an array of eight 61-m towers, a 36-m tower, a 304-m television tower, two Doppler sodars, a tethersonde system, and a sonic anemometer combined with a fast-response temperature sensor. Tracer gas (SF6) measurements were monitored continuously at 10 to 25 km by mobile gas sampler (analyzer) systems. Also, LLNL used an atmospheric release assessment model using tracer release information during the test period. Analysis of the meteorological data focused on sporadic turbulent episodes, in particular, those affected by strong wind direction shear that penetrated to the surface layer (for example, Parker and Raman (1993) report in a case study on the structure of the nocturnal boundary layer during Project STABLE). Analysis of the gas tracer measurements focused on the state of the SBL and its influence on downwind plume characteristics (e.g., broadening, overlapping, looping, and meander).

5.1.3 *First Look At Turbulent Kinetic Energy Experiment (FLAT 90)*

The First Look At Turbulent (FLAT 90) kinetic energy experiment was conducted from September through November 1990 using the NCAR Atmospheric Surface Turbulent Exchange Research (ASTER) facility at a site near Carpenter, Wyoming (Businger et al, 1990, and Oncley, 1998). Investigators from the NCAR Atmospheric Technology Division (ATD) and Mesoscale Meteorological Modeling (MMM) group, NOAA Wave Propagation Laboratory (WPL), and the Colorado State University Atmospheric Sciences Department attempted to make direct measurements of each component of the turbulent kinetic energy (TKE) budget equation in the atmospheric surface layer (Oncley et al, 1996). Propeller-vane, hot-wire, and sonic anemometers; platinum temperature sensors; Krypton hygrometers; and fast-response pressure sensors were used to measure these components (e.g., pressure transport, turbulent transport, buoyant production, shear production, dissipation). A 915-MHz wind-profiling radar, an acoustic sounder, an array of nine microbarographs, a 3×3 array of NCAR portable automated mesonet (PAM) stations (spaced every 2 mi), and several balloon soundings were also used during the test to examine gravity waves and horizontal temperature advection in the boundary layer.

5.1.4 *Flatland 95, Flatland 96, and Lidars In Flat Terrain (LIFT) Experiments*

Two boundary-layer field experiments, Flatland 95 and Flatland 96, were conducted by researchers from the University of Colorado Cooperative Institute for Research in Environmental Sciences (CIRES), the NOAA Aeronomy Laboratory, and NCAR from August to September 1995 and from June to August 1996. The Flatland experiments (Angevine et al, 1998) took place in Illinois, near Champaign-Urbana, over a flat and uniform area. The two main objectives of these tests were (1) to collect data to measure the development and structure of the top of the CBL, to include the fluxes and velocities associated with entrainment, and (2) to test and evaluate boundary-layer instrumentation and measurement techniques associated with remote sensing systems, in particular, vertical velocity measurements and turbulent heat-flux measurement using eddy correlation, radar, lidar, and acoustic sounders. Better understanding of the mixing of heat, moisture, and chemical contaminants through the CBL inversion zone due to entrainment is very important for modeling and simulation of the boundary layer. Instrumentation used during the Flatland studies included three 915-MHz boundary-layer wind profilers, each configured with a radio-acoustic sounding system (RASS) to also measure profiles of virtual temperature, two balloon-sonde sounding systems, surface meteorology stations to measure wind speed and wind direction, temperature, pressure, rainfall, and relative humidity data, three flux-PAM (portable automated mesonet) systems to measure net and incoming solar radiation, soil temperature, ground flux, sensible heat and latent heat fluxes, ozone deposition flux, and a ceilometer to provide cloud base and backscatter profile data.

The Lidars In Flat Terrain (LIFT) experiment was conducted from July to August 1996 as a companion study to Flatland 96. The LIFT experiment centered around three different types of lidar measurements, that is, from a high-resolution Doppler lidar, a scanning aerosol backscatter lidar, and a UV differential absorption lidar, used to investigate temporal and spatial variations in boundary-layer height, turbulence, fluxes, and entrainment (Cohn et al, 1998). Given the high-resolution capabilities of these relatively new remote sensing systems for boundary-layer research, the scientific objectives for the LIFT program included measuring the energy and ozone budgets, measuring the growth and decay of the boundary-layer top, characterizing the entrainment zone, and observing features of the nighttime stable layer. Additional experimental goals focused on evaluating the performance of several of the measurement techniques used during the LIFT and Flatland field operations as part of an intercomparison (lidar vs radar) study. Analysis of the LIFT data was performed to study cloud and storm formation, transport and diffusion of mixed-layer gases, and the surface energy budget.

5.1.5 *Boundary Layer Experiment 1996 (BLX96)*

The Boundary Layer Experiment 1996 (BLX96) was conducted from 15 July through 13 August in Oklahoma and Kansas to study daytime convective mixed-layer and boundary-layer cumulus clouds (Stull et al, 1997). Scientists from the University of British Columbia (UBC) performed measurements of temperature, moisture, and momentum flux profile structure using the University of Wyoming King Air aircraft as the primary instrument platform. This aircraft made 12 research flights over three sites of different land use: forest, rangeland, and crops (Stull et al, 1997). BLX96 coincided with the DOE Atmospheric Radiation Measurements (ARM) program that was conducted 15 July through 4 August at the Cloud and Radiation Testbed (CART) site in the southern Great Plains region of the United States. Collaborations were made with ANL and NCAR on data from several surface and remote sensor systems that included a 915-MHz boundary-layer wind profiler; an upper-air balloon-borne sounding system; an acoustic sounding system; surface weather, flux, and energy budget stations; and lidars. Analysis of these data was expected to improve the current capability in modeling the convective boundary layer for applications in storm prediction, for example.

5.2 Land-Atmosphere Interactions

5.2.1 *Hydrologic Atmospheric Pilot Experiment–Modelisation du Bilan Hydrique (HAPEX-MOBILHY)*

The Hydrologic Atmospheric Pilot Experiment–Modelisation du Bilan Hydrique (HAPEX-MOBILHY) was conducted in southwestern France beginning on 1 April 1985 for approximately 2 years, which included one special observation period (SOP) of $2\frac{1}{2}$ mo from 1 May to 15 July 1986 (Andre et al, 1986). The field program was carried out by researchers from the French Direction de la Meteorologie (DMN), the Programme National d'Etude de la Dynamique du Climat (PNEDC), the Institut National de la Recherche Agronimique (INRA), the Institut National des Sciences de l'Univers (INSU), the Centre National d'Etude Spatiales (CNES), and the Institute of Hydrology, as well as two U.S. agencies (NCAR and the NASA Ames Research Center). The 100-km^2 site was located within portions of the Adour and Leyre River basins in southwestern France. The test areas were mainly flat and were either forested or crop covered. The main objective of the HAPEX-MOBILHY program was to study the surface water budget (i.e., surface evaporation flux) and its influence on climate on the scale of general circulation models (10^4 km^2). Its objectives also included improving current knowledge of surface hydrology, testing and validating evaporation and soil moisture algorithms, and contributing to the use of data from remote sensing platforms by providing footprints of surface observations for comparison. Surface measurements

included observations of radiation and energy budget. Detailed measurements from instrumented aircraft included observations of the boundary-layer temperature, moisture, and momentum fluxes, and remotely sensed surface properties, such as surface radiance temperature, soil water, and vegetation indices. Several case studies have been conducted wherein model simulations that include calculation of the surface energy budget have been compared to observed data taken during the HAPEX-MOBILHY experiment (e.g., Kim and Ek, 1995, and Belair et al, 1998).

5.2.2 *First International Satellite Land Surface Climatology Project ISLSCP Field Experiment (FIFE)*

The First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) made satellite and ground-based meteorological observations continuously from 1987 through 1989 and conducted several intensive field campaigns (IFC) from May through November 1987 and from 23 July to 12 August 1989 over a 15- × 15-km portion of the Konza Prairie Natural Area near Manhattan, Kansas (Smith et al, 1994, Smith, 1998, and Sellers et al, 1988). Several universities and U.S. government agencies collaborated to study the nature of surface fluxes over mostly grassy land and to investigate the impact of land-air interactions on boundary-layer circulations, boundary-layer growth, and storm development. Surface flux measurements during FIFE included data from net and solar radiometers, Bowen ratio stations for sensible and latent heat flux and vertical temperature and moisture gradients, eddy correlation systems, portable automated mesonets (i.e., routine surface weather data to include rainfall amount), and soil moisture sampling. Measurements were also made using sodar and lidar systems. In addition, several instrumented research aircraft (to include the NASA C-130, NASA helicopter, NOAA Aerocommander, Canadian Twin Otter, NCAR King Air, and the University of Wyoming King Air) made measurements using thermal infrared and microwave radiometers such as a thermatic mapper (TM), modular multiband radiometer (MMR), infrared thermometer (IRT), spectral radiometer, and synthetic aperture radar (SAR). Satellite data to include advanced very high resolution radiometer/local area coverage (AVHRR/LAC) images, Landsat TM (thermatic mapper), SPOT (Systeme Pour l'Observation de la Terre) high resolution visible (HRV) images, and geosynchronous operational environmental satellite (GOES) images were also used to map the vegetation cover and radiance temperature of the site. Together, instrumented aircraft and satellite systems obtained the type of data needed to develop and test remote sensing methods and techniques for observing surface characteristics, such as horizontal rainfall, vegetation, and soil water content gradients. Data taken during FIFE have been used in several case studies aimed at improving operational weather forecast routines (Betts et al, 1993, and Betts et al, 1998).

5.2.3 *Monsoon 90*

The Monsoon 90 experiment was conducted over arid and semiarid rangelands in southeastern Arizona by several university, U.S. government, and international research laboratories and organizations to study spatial and temporal changes in soil moisture and to evaluate the role of the hydrologic cycle in land-atmospheric interactions (Kustas et al, 1991). The experiment took place from 4 to 6 June and from 23 July to 10 August 1990 during a typical "monsoon" season, over an area approximately 50 km^2, at the Walnut Gulch Experimental Watershed about 120 km southeast of Tucson, Arizona. The field program focused on measurements of surface soil moisture, surface albedo, vegetation coverage, and surface temperature from thermal and microwave sensors at or near the ground, on aircraft platforms, and from satellites. Also, multispectral instruments and IRTs were carried by experimenters on foot (using shoulder harnesses) to obtain similar types of data as those taken from aircraft sensors (e.g., multifrequency microwave radiometers, thermal imaging multispectral scanners, thermal infrared scanners, IRTs, and multispectral video cameras) and satellite (e.g., NOAA 11 and AVHRR) systems. At the same time, surface energy balance, water budget, and boundary-layer profile data were collected from eight fixed and several transportable METFLUX (meteorological energy flux) stations, one tethersonde system for profile data up to 500 m at about 10 m vertical resolution, and a radiosonde station for profile data up to 6000 m at about 20 m vertical resolution. One of the primary objectives of the Monsoon 90 project was to improve remote sensing methods for assessing surface water vapor and energy exchanges.

5.2.4 *Boardman Regional Flux Experiment*

The Boardman Regional Flux Experiment was conducted from 31 May to 19 June 1991 in northeastern Oregon, near the town of Boardman, over an area of sharp contrasts in surface heating and evaporation. The site was characterized by a large, dry, mostly flat steppe bordered by irrigated farmlands (Doran et al, 1992). Measurements of the surface radiant energy, sensible heat, and latent heat fluxes were made with an extensive array of eddy correlation and surface-based Bowen ratio stations. Surface and boundary-layer heat and moisture flux and profile data were also collected using instrumented aircraft. Additional data were taken by sodars, tethered balloons, and optical wind and turbulence (i.e., scintillometer) sensors. Also during the experiment, soil temperature and moisture data were taken using TDR (time domain reflectometry) probes. Vegetation characteristics, such as leaf area index, were also measured. Participants in the field program included researchers from the DOE Argonne National Laboratory, the Los Alamos National Laboratory, the Pacific Northwest Laboratory, the NOAA Atmospheric Turbulence and Diffusion Division (ATDD), the Illinois State Water Survey (ISWS), EG&G

Measurements, Inc. of Las Vegas, Nevada, the University of Washington (UWA), the Utah State University (USU), and the Blackland Research Center (BRC) of the Texas Agricultural Experimental Station. The principal objective of the Boardman Regional Flux Experiment was to collect a sufficient amount of energy balance data over an area of stark contrasts (at the surface) that could be applied to the problem of extrapolating limited numbers of local measurements (at the micro- or mesoscale) to area-designated values for use in global circulation and climate forecast model programs.

5.2.5 *Hydrology/Atmosphere Pilot Experiment-Sahel (HAPEX-Sahel)*

The Hydrology / Atmosphere Pilot Experiment in the Sahel (HAPEX-Sahel) was an international field program conducted primarily through one 8-wk intensive observation period (IOP) over an area approximately 110 × 110 km in the West African Sahel region in western Niger (Goutourbe et al, 1997). More than 200 participants collaborated on this field program, which was designed to collect surface water flux and energy budget data needed to develop, improve, and evaluate climate models of semiarid regions. One of the main objectives of the HAPEX-Sahel project was to investigate boundary-layer (land-atmosphere) interactions and potential feedback mechanisms that affect the generation, distribution, and frequency of storms, rainfall, and soil moisture (Taylor et al, 1997). The landscape around the test area was generally flat and the vegetation consisted mainly of annual grass and scattered trees and bushes about 3 to 4 m high. Three automatic weather stations (AWS) provided continuous measurements of temperature, winds, and humidity at 7 and 14 m, as well as the short-wave and long-wave components of the radiation balance. Also, an eddy correlation system was operated at each station to measure turbulent energy fluxes. A network of rain gauges was established within the experimental site, spaced at approximately 12.5-km intervals. Radiosondes were released at two hourly intervals during the IOP. Boundary-layer measurements also included microwave and visible-to-near infrared-sensed atmospheric and vegetation characteristics made available from four instrumented aircraft platforms. Also, Meteosat and AVHRR satellite radiometer data provided vegetation index and surface radiance information. The approach taken for the HAPEX-Sahel was established by earlier field programs of this type, such as HAPEX-MOBILHY (Andre et al, 1988) in southwestern France, the First ISLSCP Field Experiment (Smith et al, 1994; Smith, 1998) in the tall grass of the Konza Prairie in Kansas, and the European Field Experiment in Desertification Threatened Areas (EFEDA) program in northern Spain (Bolle et al, 1993).

5.2.6 *Boreal Ecosystem/Atmosphere Study (BOREAS)*

The Boreal Ecosystem/Atmosphere Study (BOREAS) was a large-scale, international, interdisciplinary field program conducted over a 1000- × 1000-km region of the northern boreal forests of Canada from 1993 to 1997 (Sellers et al, 1997). Participants from several university, U.S. government, and Canadian government laboratories and organizations collaborated to collect data to characterize exchanges of radiative energy, sensible heat, water, CO_2, and other trace gases between the boreal forest and the lower atmosphere (i.e., the boundary layer). The primary goals of the BOREAS experiment were to improve the current understanding of basic climatic processes in the boreal forest ecosystem toward (1) improving atmospheric surface and boundary-layer process models that go into global climate models (to improve ways to initialize and validate GCMs and to make climate projections more credible) and (2) to contribute toward integrating remote sensing techniques and meteorological modeling studies to expand the spatial scales of the state variables. The bulk of the surface-to-atmosphere flux measurements were made within two 50- × 50-km subregions of the experimental site located near Thompson, Manitoba (the north site) and over areas of the Prince Albert National Park, Saskatchewan (the south site). Data taken at each site included tower profile and flux measurements; wind profiler, lidar, and sodar data; hydrological data to include rainfall rate and soil moisture measurements; and biomass data such as leaf area and biomass density. Aircraft and satellite-retrieved data* included optical, thermal, and microwave scattering properties and radiance measurements from vegetation, soil, and the surface.

*Instrumentation used during the BOREAS program included the following aircraft and satellite platforms: NASA-Ames ER-2 and C-130 airborne visible-to-infrared imaging spectrometer (AVIRIS), thermatic mapper simulator (TMS), advance solid-state array spectroradiometer (ASAS), and polarization and directionality of earth's radiation (POLDER) compact airborne spectrographic imager (CASI) to detect vegetation (surface) properties, to include snow; the NASA Wallops Flight Facility UH-1 helicopter-mounted multiband modular radiometer, C-band scatterometer, and POLDER; the Ontario Remote Sensing Office Piper Chieftan CASI for sensing vegetation and surface characteristics; the NASA-Ames DC-8 and the Canada Centre for Remote Sensing airborne synthetic aperture radar (AIRSAR) for sensing vegetation and surface characteristics (to include soil moisture); the National Research Council, Canada, Twin Otter-mounted microwave radiometer (snow and soil moisture); the NOAA NWS Aerocommander-mounted gamma ray system (snow and soil moisture); the NCAR Electra, the University of Wyoming King Air, the National Research Center of Canada (NRCC) Twin Otter, the NOAA Oak Ridge LongEZ, and the NASA-GSFC PA-34 aircraft-mounted flux measurements of sensible and latent heat, CO_2 and O_3 flux and concentrations; and the AVHRR, Landsat TM, SPOT, ERS-SAR and JRS-SAR, Radarstat, and GOES statellites for land cover, biomass, albedo, surface radiance, and leaf area index data.

5.2.7 *1997 Cooperative Atmospheric/Surface Exchange Study (CASES-97)*

The 1997 Cooperative Atmospheric/Surface Exchange Study (CASES-97) was part of a multiyear, interdisciplinary program coordinated by a joint project office consisting of researchers from the DOE Argonne National Laboratory, NCAR, and NOAA to investigate exchanges of energy, moisture, and environmental chemistry between the surface and the lower atmosphere. Several participants collaborated in taking measurements over the Upper Walnut River Watershed near Wichita and Winfield, Kansas from 22 April through 21 May 1997 (LeMone and Grossman, 1999). The Walnut River Watershed is also located within the DOE ARM-CART research area (Coulter, 1999). The vegetation around the test area is mostly crops, grassland, and rangeland. The principal objectives of the CASES-97 experiment were to (1) quantify exchanges of energy, moisture, and CO_2 on a variety of temporal and spatial scales, (2) improve parameterizations of the numerical models of these exchanges, and (3) identify interrelations between processes in the atmosphere, biosphere, and hydrosphere (Pflaum, 1998). The experiment included measurements from a network of boundary-layer profilers (915-MHz radars), WSR-88D radars, sodars, minisodars, radiosonde release stations, surface meteorological towers, surface flux and radiation stations, stream gauges, rain gauges, and soil moisture sampling systems. Also, satellite data included topographic and land use information. Instrumented aircraft used during the experiment included the NOAA Twin Otter and the University of Wyoming King Air.

6. Nocturnal Boundary-Layer Field Projects

The nocturnal boundary-layer field projects were designed to collect large sets of experimental data with the expectation that, through analysis and modeling, new knowledge would be gained about boundary-layer processes, particularly processes related to low-level wind maxima, gust fronts, internal wave activity, and the effects from intermittent turbulence on atmospheric transport and diffusion. For example, the mixing of air parcels in very stable layers is thought to depend mainly on coherent structures, which are not well understood. Using new and more specialized types of data could result in better definitions of turbulence in the inversion layer in numerical models.

6.1 Microfronts Project

The Microfronts Project was conducted in March 1995 to collect surface-layer turbulence, flux, and profile data over a uniform and flat rangeland site near De Graf, Kansas (Sun, 1999). Participants from NCAR, Oak Ridge National Laboratory (ORNL), the University of Colorado (UCO),

Oregon State University (OSU), and Iowa State University (ISU), with funding from the National Science Foundation (NSF) and the U.S. Army Research Office (ARO), collaborated to study the mechanisms principally responsible for the transport of momentum, heat, moisture, trace gases, and other scalar contaminants in the boundary layer (e.g., gust fronts and coherent structures). The data set included measurements taken using the ASTER micrometeorological towers (see sect. 5.1.3), that is, eddy correlation data at 3 and 10 m and mean profiles of wind speed and temperature, pyranometers and pyrgeometers for both downward and reflected solar and long-wave radiation, infrared radiometers for surface radiation temperature, and two net radiometers (Mahrt et al, 1998; Howell and Sun, 1999). The data set also included measurements from an array of microbarographs used to detect gravity-wave activity in the nighttime boundary layer and to provide the type of data needed to study the relationship between waves, turbulence, and instability. Upper-air sounding data were also taken during the experiment using tethersondes, eight NWS radiosonde and rawinsonde sites, and the DOE ARM-CART wind profiler stations. The Microfronts Project's experimental goals also included testing bulk-layer models of the surface heat flux.

6.2 Low-Level Jet Experiment 1997 (JETEX-97)

The Low-Level Jet Experiment 1997 (JETEX-97) was conducted from 22 April through 22 May over the central Great Plains region of the United States to study the development of low-level jets in the nocturnal boundary layer and the location and intensity of precipitation brought about by low-level jets and mesoscale convective systems (Arritt and Segal, 1998). Scientists from ISU, NCAR, and NOAA NWS collaborated to collect data using 915-MHz microwave wind profilers (with radio-acoustic sounding system (RASS) resolved temperatures), a radiosonde upper-air sounding system (Cross-Chain Loran Atmospheric Sounding System (CLASS)), automated surface weather stations, the NOAA profiler network (404-MHz radars), and the WSR-D88 Doppler radar stations used by the CASES-97 research group (see sect. 5.2.7). The three primary JETEX sites were located at Jayton in northwestern Texas, at Vici, Oklahoma, and at Haviland, in south central Kansas, which is located about 200 km east of the Walnut River Watershed (i.e., the CASES experimental research site). These sites are located along the axis of the maximum frequency of occurrence of the low-level jet through the central Great Plains (Arritt and Segal, 1998) as determined from previous studies (e.g., Mitchell et al, 1995). The main objective of the JETEX project was to study the low-level jet as it relates to the onset of mesoscale convective systems at night at better spatial and temporal resolutions than was possible in previous studies using the NOAA 404-MHz network or the NWS upper-air sounding sites. A second objective of the project was to study the contamination of profiler data due to migratory birds. A third objective of the project was

to improve numerical representations of the low-level jet in mesoscale forecast models, such as the CSU-RAMS (Colorado State University-Regional Atmospheric Modeling System) or the PSU-NCAR (Pennsylvania State University–National Center for Atmospheric Research) MM5 models (Yang et al, 1999). The JETEX data set was also supplemented by NOAA-8, Landsat, and GOES satellite observations for detecting cloud cover and land-surface characteristics.

6.3 Stable Atmospheric Boundary Layer Experiment in Spain (SABLES 98)

The Stable Atmospheric Boundary Layer Experiment in Spain (SABLES 98) was conducted from 9 to 26 September 1998 at the Centre of Research of Low Atmosphere (Centro de Investigaciones de la Baja Atmosfera-CIBA) near the town of Valladolid in the northern Castillian Plateau. Scientists from the Spanish Meteorological Institute (Instituto Nacional de Meteorologia-INM), the University of Barcelona (UB), and the Risø National Laboratory, Denmark, collaborated to collect data to characterize continuous and intermittent turbulence structures and events in the stably stratified nighttime boundary layer. Data taken at the center of a large, flat, 80-km^2 site (referred to as Montes Torozos) included measurements from a 10- and 100-m instrumented tower, a sodar, and a tethersonde balloon system for profiles up to 1 km (Cuxart, 1999). The instrumented 100-m tower data included measurements from low-response (frequency) temperature, wind, and humidity sensors (only wind speed and wind direction up to the 100-m level), three sonic anemometers (at the 5.8-, 13.5-, and 32-m levels), a fast-response humidity flux sensor (at the 14.5-m level), an infrared surface temperature sensor (at the 3-m level), and an array of 14 thermocouples (from the surface up to the 50-m level). The 10-m surface layer tower included three sets of low-response instruments for the mean profiles of temperature, wind, and humidity (at the 2.5-, 5.5-, and 10-m levels), two sonic anemometers (at the 3.5- and 7.5-m levels), soil temperature and soil moisture sensors, and soil heat flux and net radiation instrumentation to record the surface energy budget. The tethered balloon system recorded the development of several low-level jets in the lowest 100-m layer during the field test. Optimum synoptic weather patterns on 14 and 15 September provided very stable conditions for the SABLES experiment. The primary goals of the SABLES experiment were to (1) become familiar with the Montes Torozos field site with regard to the development of the nighttime stable layer, (2) determine what statistical elements in characterizing turbulence and profile structure (i.e., similarity theory) are valid at the site, and (3) study internal gravity-wave and turbulence interactions at the site with regard to the transport of momentum, heat, and other atmospheric scalars (Cuxart, 1999).

6.4 1999 Cooperative Atmospheric/Surface Exchange Study (CASES-99)

The 1999 Cooperative Atmospheric/Surface Exchange Study (CASES-99) program consists of proposals for research from scientists at the DOE Argonne National Laboratory, NCAR, NOAA, and several university departments to conduct a field study in October of this year to focus on exchanges in the soil-biosphere-atmosphere, specifically during stable atmospheric conditions (Blumen et al, 1998). Many of the participants who were involved in the CASES-97 project (see sect. 5.2.7) will collaborate in taking meteorological and hydrological measurements over the Upper Walnut River Watershed, the DOE ARM-CART site, the ANL Atmospheric Boundary Layer Experiment (ABLE) area, and the NOAA Wind Profiler Network (WPN) research areas in southern Kansas. The CASES-99 experimental site is approximately 60 km across and is virtually flat. The main goal of the CASES-99 project is to identify, through data analysis and modeling, the processes that produce intermittent turbulence under very stable conditions (see sect. 1). Data from the experiment will include measurements from a network of boundary-layer profilers, 915-MHz radars, WSR-88D radars, lidars, sodars, minisodars, NWS radiosonde release stations, tethersondes, instrumented kite platforms, surface meteorological towers, surface flux and radiation stations, stream gauges, rain gauges, and soil moisture sampling systems. Satellite data will include topographic and land use information. Aircraft to be used during the experiment will include the NOAA Twin Otter and the University of Wyoming King Air. Also, there are plans to support very high resolution (on the order of 1 m) FM-CW radar measurements of the refractive index structure parameter and visualization of nocturnal boundary-layer phenomena, such as microfronts and Kelvin-Helmholtz wave structures. The CASES-99 data are expected to provide time histories of wave and turbulence activity within the stable layer and measurements of the heat flux (and flux divergence) in the lowest 10 to 20 m above ground level. Analysis of the data from the CASES-99 project is expected to focus on (1) conditions when $Ri \geq 1.0$, where Ri is the Richardson number,* and (2) the boundary-layer portions of mesoscale forecast models.

*The Richardson number can be expressed in terms of the ratio of the vertical temperature gradient and the wind velocity gradient squared.

7. Summary

For the past half century, data collected through countless outdoor field experiments have been applied toward improving the theory, numerical models, and known scaling laws (i.e., similarity theory) that are used to characterize processes and events in the atmospheric boundary layer. The experimental data, generated from a very large array of in situ and remote sensor platforms, have benefited studies in air quality, cloud and storm formation, and regional and global climate. Through these previous outdoor works, a great many new meteorological sensor technologies, observational methods, and data reduction techniques have been advanced.

This author has presented a thorough academic review of some 30 previous works on observing the atmospheric boundary layer (ABL), based on a relatively broad survey of the literature on the topic of outdoor boundary-layer experiments. This report provided an overview of that study from which atmospheric science researchers who seek ABL data from previous experiments or scientists who are planning new ABL or related field programs may benefit. Also, atmospheric science historians and policymakers may have interests in this type of reporting and might find a very complete index of citations both useful and informative.

Acronyms and Abbreviations

ABL	atmospheric boundary layer
ABLE	ANL Atmospheric Boundary Layer Experiment
ACMAD	African Centre of Meteorology Applied to Development
AES	Atmospheric Environment Service, Downsview, Canada
AFCRC	Air Force Cambridge Research Center
AFCRL	Air Force Cambridge Research Laboratory
AGRHYMET	Agricultural, Hydrology, and Meteorology Centre of the Sahel
AIRSAR	airborne synthetic aperture radar
AL A&M	Alabama Agricultural & Mechanical University
ANL	Argonne National Laboratory
ARL	U.S. Army Research Laboratory; NOAA Air Resources Laboratory
ARM	Atmospheric Radiation Measurements program
ARO	U.S. Army Research Office
ARS	USDA Agricultural Research Service
ASAS	advance solid-state array spectroradiometer
ASCOT	Atmospheric Studies in Complex Terrain
ASTER	Atmospheric Surface Turbulent Exchange Research facility
ATD	Atmospheric Technology Division
ATDD	NOAA Atmospheric Turbulence and Diffusion Division
AUW	Agricultural University of Wageningen
AVE	Atmospheric Variability Experiments
AVHRR	advanced very high resolution radiometer
AVIRIS	airborne visible-to-infrared imaging spectrometer
AWS	Air Weather Service
BAO	Boulder Atmospheric Observatory
BLX83	Boundary Layer Experiment 1983
BLX96	Boundary Layer Experiment 1996
BMO	British Meteorological Office
BNL	Brookhaven National Laboratory
BOREAS	Boreal Ecosystem/Atmosphere Study

BRC	Blackland Research Center (of the Texas Agricultural Experimental Station)
CART	cloud and radiation testbed
CASES	Cooperative Atmospheric/Surface Exchange Study
CASI	compact airborne spectrographic imager
CBL	convective boundary layer
CBM	Commonwealth Bureau of Meteorology
CCRS	Canadian Center for Remote Sensing, Ottowa
CEMAGREF-ENGREF	Centre National du Machinisme Agricole, du Génie Rural, des Eaux et des Forêts–Ecole Nationale du Génie rural des Eaux et des Forêts (French Institute of Forestry, Agricultural and Environmental Engineering)
CESBIO	Centre d'Etudes Spatiales de la Biosphere
CEWCOM	Cooperative Experiment for West Coast Oceanography and Meteorology
CIBA	Centre of Research of Low Atmosphere–Centro de Investigaciones de la Baja Atmosfera
CIRES	Cooperative Institute for Research in Environmental Sciences
CLASS	Cross-Chain Loran Atmospheric Sounding System
CNES	Centre National d'Etude Spatiales
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSU	Colorado State University
CU	Cornell University
DLO	Agricultural Research Organization of The Netherlands
DMN	French Direction de la Meteorologie
DOE	Department of Energy
DRI	Denver Research Institute
EFEDA	European Field Experiment in Desertification Threatened Areas
EG&G	EG&G Measurements, Inc. of Las Vegas, Nevada
EPA	Environmental Protection Agency
ERL	Environmental Research Laboratory
ETL	Environmental Technology Laboratory
FC	Forestry Canada, Edmonton, Alberta

FIFE	First ISLSCP Field Experiment
FLAT	First Look At Turbulent kinetic energy experiment
FM-CW	Frequency Modulated-Continuous Wave
GCM	global climate model
GOES	geosynchronous operational environmental satellite
GSFC	NASA Goddard Space Fight Center
HAPEX-MOBILHY	Hydrologic Atmospheric Pilot Experiment–Modelisation du Bilan Hydrique
HAPEX-Sahel	Hydrology/Atmosphere Pilot Experiment in the Sahel
HRV	high resolution visible
IAP	Institute of Atmospheric Physics
IBS	Institute of Behavioral Sciences
IFC	intensive field campaigns
IH	Institute of Hydrology
INM	Spanish Meteorological Institute (Instituto Nacional de Meteorologia)
INRA	Institut National de la Recherche Agronimique
INSU	Institut National des Sciences de l'Univers
IOP	intensive observation period
IRE	USSR Academy of Sciences Institute of Radioengineering and Electronics
IRT	infrared thermometer
ISC	Iowa State College
ISLSCP	International Satellite Land Surface Climatology Project
ISU	Iowa State University
ISWS	Illinois State Water Survey
ITCE	International Turbulence Comparison Experiment
JETEX-97	Low-Level Jet Experiment 1997
JHU	Johns Hopkins University
JPL	Jet Propulsion Laboratory
KNMI	Royal Netherlands Meteorological Institute
KSU	Kansas State University
KU	Kyoto University

LA	Laboratoire d'Aerologie
LAC	local area coverage
LANL	Los Alamos National Laboratory
LERTS	Laboratoire d'Etudes et de Recherches en Teledetection Spatiale
lidar	light detection and ranging
LIFT	Lidars In Flat Terrain experiment
LLNL	Lawrence Livermore National Laboratory
METEO-FRANCE	Public Meteorological Service of France
METFLUX	meteorological energy flux station
METROMEX	Metropolitan Meteorological Experiment
MIT	Massachusetts Institute of Technology
MMM	Mesoscale Meteorological Modeling group
MMR	modular multiband radiometer
MRI	Meteorological Research Institute
MRU	Meteorological Research Unit
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCSU	North Carolina State University
NESDIS	National Environmental Satellite Data Information Service
NOAA	National Oceanic and Atmospheric Administration
NRCC	National Research Center of Canada
NRL	Naval Research Laboratory
NSERC	Natural Sciences and Engineering Research Council, Canada
NSF	National Science Foundation
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
Offutt AFB	Offutt Air Force Base
ONR	Office of Naval Research
ORNL	Oak Ridge National Laboratory
ORSTOM	French Institute of Scientific Research for Development

OSU	Oregon State University
OU	Okayama University
PAM	portable automated mesonet
PILPS	Project for the Intercomparison of Land/Surface Parameterization Schemes
PNEDC	Programme National d'Etude de la Dynamique du Climat
PNL	Pacific Northwest Laboratory
POLDER	polarization and directionality of earth's radiation
PSU	Pennsylvania State University
PU	Princeton University
radar	radio detection and ranging
RAOB	radiosonde observation
RASS	radio-acoustic sounding system
Ri	Richardson number
Risø	Risø National Laboratory, Denmark
SABLES	Stable Atmospheric Boundary Layer Experiment in Spain
SAR	synthetic aperture radar
SBL	stable boundary layer
SESAME	Severe Environmental Storms and Mesoscale Experiment
sodar	sonic detection and ranging
SOP	special observation period
SPOT	Systeme Pour l'Observation de la Terre
SRI	Stanford Research Institute
SRL	Savannah River Laboratory
STABLE	Stable Boundary Layer Experiment
Stewart AFB	Stewart Air Force Base
TAC	Tactical Air Command
TDR	time domain reflectometry
Texas A&M	Agricultural and Mechanical College of Texas
TKE	turbulent kinetic energy
TM	thermatic mapper
TMS	thermatic mapper simulator

UAD	University of Adelaide
UAZ	University of Arizona
UB	University of Barcelona
UBC	University of British Columbia
UCAR	University Center for Atmospheric Research
UCD	University of California at Davis
UCH	University of Chicago
UCLA	University of California at Los Angeles
UCO	University of Colorado
UCSD	University of California at San Diego
UG	University of Georgia
UM	University of Maryland
UMR	University of Missouri at Rolla
UNE	University of Newcastle
UNI	University of Niamey
UNL	University of Nebraska-Lincoln
UO	University of Oklahoma
UOP	University of Osaka Prefecture
UP	Universite de Provence
USFS	U. S. Forest Service
USGS	U. S. Geological Survey
USU	Utah State University
UT	University of Texas
UVA	University of Virginia
UWA	University of Washington
UWI	University of Wisconsin
UWY	University of Wyoming
WADC	Wright Air Development Center
WHOI	Woods Hole Oceanographic Institution
WPL	Wave Propagation Laboratory
WPN	NOAA Wind Profiler Network

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Acknowledgment

The author gratefully acknowledges the expert personnel of the Adelphi Laboratory Center Technical Library for their support in retrieving numerous reports, journal articles, and textbook materials needed to complete this task. The author also thanks Drs. Teizi Henmi and Sam Chang for their time in reviewing this work and for offering valuable comments.

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3. REPORT TYPE AND DATES COVERED Final, 10/26/98–4/16/99

4. TITLE AND SUBTITLE A Review of Previous Works on Observing the Atmospheric Boundary Layer Through Meteorological Measurements

5. FUNDING NUMBERS
DA PR: B53A
PE: 61102A

6. AUTHOR(S) Arnold Tunick

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Attn: AMSRL- IS-EM email: atunick@arl.mil
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-MR-448

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
ARL PR: 9FEJ70
AMS code: 611102.53A

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report provides a comprehensive review of some 30 previous works on observing the atmospheric boundary layer through meteorological measurements. I compiled the information in this report from a relatively broad survey of the literature related to field experiments that had focused on processes and events that characterize the boundary layer, and in particular, the boundary layer under atmospherically stable conditions. The summaries that comprise the bulk of the report provide the reader with historical as well as data resource information for several different types of programs on topics from improving weather and climate prediction models to advancing remote sensing platforms and monitoring techniques. Also, the report presents some of the main conclusions derived from two workshop meetings on turbulence and diffusion in the stable boundary layer.

I wrote this report as a result of studying and annotating about 90 references and texts on experiments in the atmospheric boundary layer. It was produced during a period preceding the Cooperative Atmospheric/Surface Exchange Study (CASES-99) program. A colleague suggested that researchers and experimental planners at the Army Research Laboratory might benefit from such an accounting of the scientific objectives, technical goals, and descriptions of the arrays of various sensor platforms that were involved with previous outdoor programs.

14. SUBJECT TERMS
Atmospheric boundary layer, field experiments, micrometeorology

15. NUMBER OF PAGES
54

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

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